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Temporal judgments in multi-sensory space

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Temporal judgments in multi−sensory space

Highlights

- Sounds are not always "longer than lights"
- Spatially changing stimuli result in temporal overestimation in vision
- The overestimation bias may derive from an error-correction mechanism
- This mechanism fails in mixed-modality trials due to cross-modality time integration

Abstract

To successfully interact with the environment requires a combination of stimulus recognition as well as localization in both space and time, with information moreover coming from multiple senses. Several studies have shown that auditory stimuli last subjectively longer than visual ones of equal duration. Recently, it has also been suggested that stimulus position affects duration perception. The present study investigated how lateral spatial presentation influences sub-second visual and auditory duration judgments. Five experiments were conducted using the duration discrimination paradigm, wherein two stimuli are presented sequentially and participants are asked to judge whether the second stimulus (comparison) is shorter or longer in duration than the first (standard). The number of stimulus positions and the way in which different modality trials were presented (mixed or blocked) varied. Additionally, comparisons were made either within or across modalities. No stable effect of location itself was found. However, in mixed modality experiments there was a clear over-estimation of duration in visual trials when the location of the comparison was different from the standard. This effect was reversed in the same location trials. Auditory judgments were unaffected by location manipulations. Based on these results, we propose the existence of an error-mechanism, according to which a specific duration is added in order to compensate for the loss of duration perception caused by spatial attention shifts between different locations. This mechanism is revealed in spatial and modality-mixed circumstances wherein its over-activation results in a systematic temporal bias.

Keywords: visual, auditory duration, location, spatial attention, duration discrimination

1. Introduction

Every cognitive process includes a temporal aspect, but the way duration is perceived is highly context specific (Eagleman, Tse, Buonomano, Janssen, Nobre & Holcombe, 2005). Both the properties of the target stimulus (e.g. brightness or loudness) and the physiological or attentional state of the participant can have an effect on the subjective duration of events (Wearden, Todd & Jones, 2006; Naish, 2014; Burle & Casini, 2001). For example, brighter stimuli are usually judged as longer in duration than less bright ones (Brigner, 1986; Rammsayer & Verner, 2014; Xuan, Zhang, He & Chen, 2007) Furthermore, attending to stimuli often results in their temporal overestimation (New & Scholl, 2009; Yeshurun & Marom, 2008; Coull, Vidal, Nazarian & Macar, 2004).

One of the major factors affecting the subjective duration of stimuli is the sensory modality involved, which influences both perceived duration and accuracy of temporal judgments (Droit-Volet & Wearden, 2002 ; Walker & Scott, 1981). It has even been suggested that the auditory modality is the "default" modality for timing (Romei et al., 2011; Chen & Yeh, 2009). Estimating the duration of an auditory event is generally a more accurate process than doing the same for a visual one (Burr & Alais, 2006). Furthermore, it seems that task-irrelevant auditory temporal intervals affect the duration perception and increase the discrimination sensitivity of relevant visual stimuli (Bausenhart, De la Rosa & Ulrich, 2014; Klink, Montijn & van Wezel, 2011). The reverse effect (irrelevant visual intervals affecting the duration perception of auditory ones) is also observed, but it is considerably weaker (Bausenhart, De la Rosa & Ulrich, 2014). Similarly, coupling visual stimuli with auditory cues that occur in close temporal proximity enhances performance on visual temporal order judgments (Hairston, Hodges, Burdette & Wallace, 2006). These effects would be expected given that auditory perception relies heavily on fine temporal resolution of stimuli, while visual perception is better suited to fine spatial judgements (Guttman, Gilroy, & Blake, 2005).

However, the relative inaccuracy of temporal judgements in the visual modality appears not simply to comprise greater variance about an accurate mean; rather, a consistent bias has been observed, often expressed as “sounds seem longer than lights”. In other words, if a visual and an auditory stimulus of equal duration are presented, the visual event will be judged shorter. Wearden et al (1998) attributed these findings to a faster rate of a putative internal clock for auditory than for visual stimuli.

Internal clock models are commonly used to explain conscious temporal judgments (Gibbon, 1977). These models conceive of a clock mechanism consisting of a pacemaker that generates regular pulses and an accumulator that counts them. The sum can then be compared to stored representations, to derive an estimate of relative duration. To account for observed inaccuracies, it has been proposed that errors may occur in any of these components: the pacemaker rate may change, the accumulator may miss ticks or count neural noise, and the stored interval representation may suffer distortions (Hansen & Trope, 2012; Ulrich, Nitschke & Rammsayer, 2006; Droit-Volet, Meck & Penney, 2007). According to Wearden (1999), more pulses are counted during the processing of sounds and therefore the auditory temporal intervals are overestimated in comparison to the visual ones. This difference in pulse count has predominantly been attributed to the rate of the auditory pacemaker being higher than that of the visual pacemaker (Chen & Yeh, 2009; Klink et al., 2011). This rate difference could be explained in terms of the existence of modality specific timing systems, with a faster ticking clock in the auditory system than the visual. Such an explanation would be compatible with the theory according to which timing is dependent on the processing of local neural circuit and therefore can differ across modalities (Ivry & Schlefr, 2008). An alternative explanation would be to assume the existence of a central amodal clock, but with the two kinds of stimuli attracting different levels of attention.

Although Wearden, Todd & Jones (2006) report these modality differences when the auditory and visual stimuli are presented in different blocks, the effect is more commonly observed when the stimuli are intermixed (Penney, Gibbon & Meck, 2000). This has been explained within the common clock account in terms of a "memory mixing" mechanism. When different modality stimuli are mixed, participants may adopt a strategy, which employs a single unified interval representation, formed as a combination of both the visual and auditory stimuli. The value of this "common" stimulus is somewhat low for the auditory modality, but too large for the visual, hence leading to "long sound/short light" responses. The experiments presented here specifically assessed the alleged mixed/blocked differences upon timing accuracy and their implication for the nature of the underlying timing mechanisms.

The above modality effects have so far been observed with centrally presented stimuli. However, recently it has been suggested that the spatial position of stimuli can influence temporal judgments (Oliveri, Koch & Caltagirone, 2009, Vicario, Caltagirone & Oliveri, 2007). Interestingly, if two visual stimuli of equal duration are presented, the first in one hemi-field, the second in the other, they are likely to be judged as unequal (Vicario et al., 2008). The right side of space has been reported to elicit longer duration judgments and the left side to produce shorter judgments (Vallesi, Binns, & Shallice, 2008). The present study was the first one to date to investigate the effect of lateral stimulus presentations in both the visual and auditory modality.

The reported left-right differences in duration perception hint at the existence of multiple timing systems. In terms of internal clock accounts, these differences could be attributed to the existence of separate clocks in each hemisphere. If stimuli to the left are judged as shorter, this would represent the clock in the right hemisphere ticking more slowly than in the left (Naish, 2014). It has been shown that hypnosis engenders a shift towards right hemispheric dominance (Naish, 2010). In addition, hypnotized people exhibit significantly distorted time judgments, the changes being in the direction that would be explained by a slowing clock (Naish, 2014). Alternative explanations could postulate a single clock, but two accumulators, one in each hemisphere. Whatever the explanation, any hemispheric division of this sort may be expected to lead to differing time estimates when lateralized auditory stimuli are used in place of visual stimuli.

Spatially selective temporal mechanisms have also been suggested by adaptation studies, which have postulated that temporal perception could take place independently in different regions of the visual field (Johnston, 2010). For example, after adapting to visual flicker in one region of visual space, a test stimulus appearing in that location is judged to be of significantly shorter duration (Johnston, Arnold, & Nishida, 2006). However, this may be linked to the inhibition-of-return effect (e.g. Martín-Arévalo, Kingstone, & Lupiáñez, 2013) and may reveal more about the effects of localised attention than localised temporal mechanisms. The longer-to-the-right effect could also be explained as resulting from a tendency to spatially represent time by means of a mental time line (MTL) as analogous to a typical number line where magnitude increases in the rightward direction (Walsh, 2003). Similar spatial effects in visual and auditory duration estimations could then indicate the existence of a supramodal mental time line.

In the context of the connection between spatial and temporal processing, it is interesting to consider the effects of saccades on timing (Morrone, Ross & Burr, 2005). The duration of a visual stimulus that follows a saccade is often overestimated, a phenomenon known as "chronostasis" (Yarrow, Haggard, Heal, Brown & Rothwell, 2001). Chronostasis is thought to be the result of a mechanism compensating for the time "lost" during saccades (Yarrow, 2010). It is conceivable that similar error correction mechanisms may be implicated in other aspects of disrupted temporal perception as shall be suggested in the Discussion.

The present study quantified the differences between visual and auditory sub-second duration judgments of stimuli presented on the right and the left side in a series of five experiments. The duration discrimination task was employed with filled visual and auditory intervals. The number of spatial positions and the presentation of visual and auditory stimuli were varied across experiments. Specifically, we investigated whether the presentation of stimuli on the right would lead to overestimation of durations and the presentation on the left would lead to underestimations in both visual and auditory modalities. We hypothesized that if there is a central supramodal clock, then similar left/right differences would be observed in the visual and auditory modalities. However, we were expecting smaller magnitude of biases in the auditory modality because of the general higher precision in auditory duration judgments. Furthermore, we investigated whether the lateral presentation of stimuli would modulate the previously reported modality effect of "sounds being judged as longer than lights".

2. Experiments 1 & 2

2.1. Introduction

Experiment 1 involved visual and auditory trials presented in separate blocks. The initial aim of this experiment was to determine whether an over-estimation of durations of stimuli within the right side of space and an under-estimation of such for stimuli within the left side would be present for auditory stimuli, and to detect any differences between the sensory modalities (Vicario et al., 2008; Frassinetti, Magnani & Oliveri, 2009).

Experiment 2 had exactly the same structure as Experiment 1, except that the visual and auditory trials were randomly intermixed. This experiment tested whether a change from blocked to mixed modality presentation would affect the psychophysical functions in a similar way to previous studies – thus, if it would lead into an overestimation of auditory judgments compared to the visual ones (Wearden et al., 2006). In addition it was assumed that the random pattern of switching between modalities would impose a greater attentional demand. It has been shown that varying the modality presentation of trials of a single task induces slower reaction times and impairs participants' accuracy in the modality switch trials (Murray et al., 2009; Gondan et al., 2004; Hunt & Kingstone, 2004). It has also been proposed that increasing the cognitive load affects temporal processing (Chen & O'Neill, 2010), so it was possible that other effects, such as the left/right difference, may be revealed.

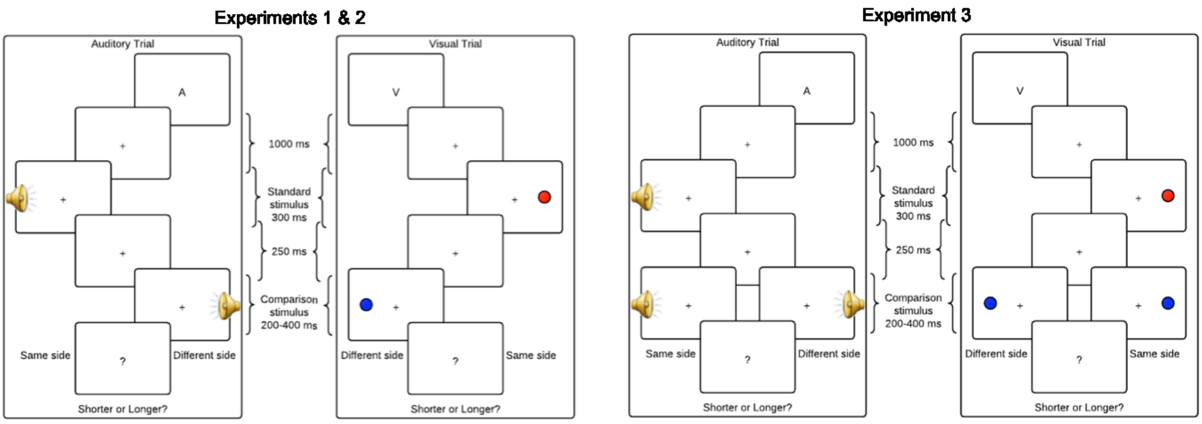

Figure 1. Time course & stimuli of Experiments 1, 2 & 3

2.2. Methods

2.2.1. Participants

Twenty-five healthy adults participated in Experiment 1 (14 female and 11 male students at the University of Edinburgh; aged 18-28; mean±SD = 24.6±3.9yrs.) and 24 in Experiment 2 (13 female and 11 male (aged 18-28; mean±SD = 23.8±3.2yrs)). The data of 3 participants in Experiment 1 and 2 participants in Experiment 2 were excluded from the analysis due to a high level of inaccurate responses[1].

2.2.2. Apparatus and Stimuli

A PC with a colour monitor controlled the presentation of the stimuli, and it was located approximately 60 cm in front of the participants. The experimental program was designed in E-Prime 2 (Psychology Software Tools). The stimuli were filled visual or auditory intervals. The visual stimuli were pure blue or red circles of 1° width presented on the left or the right side of the screen (8° eccentricity from the center of the circle to the center of the screen) on a white background. Auditory stimuli were pure tones of 440 Hz and they were presented monaurally via headphones at an intensity of 75 dB SPL.

2.2.3. Procedure

In the duration discrimination paradigm a standard stimulus is first presented, followed after a short interval by the comparison stimulus. The latter is selected from a range of durations, some shorter and some longer than the standard. Using binary forced choice responses, participants are required to decide whether the comparison was shorter or longer. The time course of the trials is represented in Figure 1. The initial presentation of “V” or “A”, was employed only in Experiment 2. In Experiment 1, the visual trials started with the presentation of a fixation cross in the centre of the screen, which remained visible throughout the stimulus presentations. Participants were asked to fixate on the cross and not to move their eyes throughout the trial. After 1000 ms, the standard stimulus (red circle for half the participants, blue for the others) was presented for 300 ms. Half the trials started with a left

[1] The average of the percentage of accuracy performance was calculated across subjects. Participants whose performance accuracy was 2 standard deviations below the mean accuracy of the group were excluded.

side presentation, whilst the other half started with a right side presentation. The inter-stimulus interval (ISI) between the standard and the comparison was 250 ms. Ten different comparison durations were used, ranging from 200 ms to 400 ms with a constant step size of 20 ms, excluding 300 ms. Thus, the randomly selected comparison had a 50/50 chance of being longer or shorter in duration than the standard. The comparison stimulus, a second circle in the opposite colour, was always presented laterally opposite with respect to the preceding standard. This resulted in having two spatial position conditions, Left – Right (LR) and Right – Left (RL) with participants performing 160 trials in each condition. The different position trials were randomly intermixed. On the offset of the comparison stimulus the fixation cross was replaced by a question mark, prompting participants to indicate whether the comparison had seemed shorter or longer than the standard. Responses were made using the M and K keys of the PC, M representing a shorter decision. The structure of the auditory block was similar to the visual, but instead of circles on the left and right side of the screen, participants were presented with a tone to either the left or right ear. The fixation cross was still used, to serve as a warning, and the question mark signaled the need for a response. A complete session consisted of 20 practice trials followed by 320 experimental trials for each of the two blocks. The order of the two blocks was counterbalanced between participants. In Experiment 2 visual and auditory trials were intermixed, but the experiment was in other respects indistinguishable from Experiment 1. Each trial started with a cue, indicating the modality of the next trial. A capital “V” was the cue for a visual trial and a capital “A” the cue for auditory. The cue remained on the screen for 1000 ms.

2.2.4. Data processing

The probability of a stimulus being judged longer was plotted against the duration of the comparison stimulus (generating a characteristic sigmoid curve). The steepness of the central section provides a measure of the participant’s sensitivity to duration changes (an ideal observer would produce a step function) and the mid-point (50% *longer* responses) represents the point of subjective equality of the two stimuli (PSE). In our experiment these parameters were calculated for each participant in each test condition, by using logistic regression of the proportions of *longer* responses (Droit-Volet, Tourret & Wearden, 2004). Sensitivity to duration differences was measured by calculating the Weber ratio (WR)[2], which is the difference limen (DL= just noticeable difference) divided by the PSE value. The DL is defined as half the difference in duration between the comparison stimulus that gives rise to 75% of longer responses and the comparison stimulus that gives rise to 25% of longer responses (Droit-Volet & Rattat, 2007). Smaller WRs indicated greater sensitivity to duration differences.

2.3. Results

2.3.1. Experiment 1

Fig. 2a shows the mean proportion of *longer* responses plotted against the durations of the comparison stimulus for the different modalities and the different location sequences. As expected, the number of *longer* judgments was small when the comparison duration was at its shortest, while the longest comparison stimuli elicited a high proportion of *longer* responses. Fig. 2a also suggests that visual stimuli are judged less accurately than auditory. The statistical significance of the differences between the probabilities of making a *longer* decision was tested using a 10 (duration) x 2 (location sequence: LR vs RL) x 2 (modality: V vs A), repeated measures ANOVA. In this and all the subsequent experiments, where the sphericity assumption was violated, corrected degrees of freedom were substituted, using Greenhouse-Geisser estimates. There was an effect of comparison stimulus duration,

[2] We used WRs instead of the Just Noticeable Difference (JND) measure as we wanted to be able to directly compare the results of our study to the previously conducted study by Wearden at al. (2006).

($F(2.36,49.65)=232.35$, $p<.001$, $\eta^2_p=.92$), and also a significant modality by stimulus duration interaction, ($F(2.47,51.88)=18.9$, $p<.001$, $\eta^2_p=.47$). This interaction indicates a larger rate of increase of *longer* responses with duration in the auditory modality. To specifically test the effect of location, separate repeated measures ANOVAs in the Visual and Auditory modality were conducted. Only duration was found to have a significant effect in either visual or auditory comparisons, Visual, ($F(1.8,39.2)=58.31$, $p<.001$, $\eta^2_p=.73$) and Auditory, ($F(3.3,69.7)=319.17$, $p<.001$, $\eta^2_p=.94$).

The PSE values for the different experimental conditions are shown in Fig. 2b. An ANOVA performed on the PSEs found no significant effect of either modality or position ($\mu=299$ for visual LR & $\mu=304$ for visual RL and $\mu=294$ for auditory LR & $\mu=298$ for auditory RL). However, WRs were considerably lower for the auditory conditions ($\mu=0.042$ for LR and $\mu=0.044$ for RL) than for the visual ($\mu=0.085$ for LR and $\mu=0.084$ for RL). A repeated measures ANOVA on WRs showed a main effect of modality, ($F(1,21)=12.46$, $p<.01$, $\eta^2_p=.37$) .

2.3.2 Experiment 2

Fig. 2c shows the psychophysical functions in the visual and auditory trials. As before, a repeated measures ANOVA, with three factors, modality (V vs A), location (LR vs RL) and duration (10 comparison durations), was conducted in order to test the significance of the differences between the probabilities of making a longer decision. The ANOVA showed effects of stimulus duration, ($F(2.17, 45.5)=424.65$, $p<.001$, $\eta^2_p=.95$) and modality, ($F(1, 21)=5.04$, $p<.05$, $\eta^2_p=.2$). The visual trials contained a higher proportion of *longer* responses. Also, the interaction between modality and duration was found to be significant, ($F(4.07, 85.6)=36.01$, $p<.001$, $\eta^2_p=.63$) indicating again a steeper central section for the auditory functions. Separate repeated measures ANOVAs in the visual and auditory modality were then conducted. In both only the effect of duration was found to be significant: for visual,

($F(2.23, 46.8)=130.57$, $p<.001$, $\eta^2_p=.86$) and for auditory, ($F(3.07, 64.62)=585.35$, $p<.001$, $\eta^2_p=.96$).

The PSEs for the different experimental conditions are shown in Fig. 2d. A repeated measures ANOVA, with modality and location as factors, showed a significant effect of modality, ($F(1,21)=5.93$. $p<.05$, $\eta^2_p=.22$). Post-hoc t-tests showed that visual RL ($\mu=282$) was significantly smaller than auditory RL ($\mu=301$), ($t(21) = -2.65$, $p<.01$, Cohen's $d= -.69$) and there was a trend towards significance for visual LR ($\mu=286$) to be smaller than the auditory LR ($\mu=296$), ($t(21) = -2.02$, $p=.076$, Cohen's $d = -.51$). The findings suggest that participants tended to overestimate the visual trials.

WRs were lower for the auditory conditions ($\mu=0.034$ for LR and $\mu=0.035$ for RL) than for visual ($\mu=0.084$ for LR and $\mu=0.091$ for RL). As in Experiment 1, conducting a repeated measures ANOVA revealed a significant effect of modality, ($F(1,21)=24.36$, $p<.001$, $\eta^2_p=.54$), showing again that participants had higher temporal sensitivity in the auditory modality.

2.4. Interim Discussion

No effect of lateral presentation was observed in either Experiment 1 or 2. Furthermore, in Experiment 2, surprisingly, we observed an overestimation of visual trials in comparison to the auditory ones. This pattern is the opposite that the one reported in previous studies – larger proportion of *longer* judgments during auditory trials (Wearden, Todd & Jones, 2006).

One of the main differences between our study and the previous ones was our use of a changing location for stimulus presentation. In the current study, the participants needed to monitor two separate locations and shift their attention between them. Hence, the disparity in results could be attributed to transient shifts of spatial attention between the two stimuli. In order to test this hypothesis, a third experiment was conducted involving two additional position sequences.

3. Experiment 3

3.1. Introduction

In Experiment 3, after the first stimulus was presented (left or right), the second could appear either on the same or opposite side of the screen (or ear for auditory stimuli). We predicted that in the *change of location* trials participants would, as in Experiment 2, continue to overestimate the visual stimuli in comparison to the auditory. However, in the *same location* trials underestimation of visual stimuli (or possibly no differences) would be anticipated.

3.2. Methods

3.3.1. *Participants*

Participants were students of the University of Edinburgh, 15 female and 13 male, aged between 18 and 29 years (*M* = 24.9, *SD* = 2.8). The data of 4 participants were excluded from the analysis due to high level of inaccurate responses (the criteria for exclusion were the same as in Experiment 1). Therefore, data from 24 participants were analysed.

3.3.2. Apparatus and Stimuli

The apparatus was the same as in Experiments 1 and 2.

3.3.3. Procedure

The structure of Experiment 3 was similar to that of the Experiment 2 but “same side” conditions were added. In half the trials the standard and comparison stimuli were presented on the same side of the screen (or at the same ear) and in the remaining trials on the opposite side (or different ear). This resulted in having four levels of spatial position for each modality, Left – Left (LL), Left-Right (LR), Right-Right (RR), Right-Left (RL). The different modality and position trials were randomly intermixed, with 80 trials of each; this resulted in a total of 640 trials.

3.3.4. Data processing

Data processing was the same as in Experiments 1 and 2.

3.3. Results

Fig. 2e shows the psychophysical functions for the visual and auditory trials. Since there was no significant difference between left and right locations, only between *same location* and *change of location* conditions, the functions shown in the graph combine same location (RR & LL) data and different location (LR & RL) data. A repeated measures ANOVA was conducted, with modality (V vs A), location (RR, LL, LR & RL) and duration (10 comparison durations) as factors. This revealed main effects of modality, ($F(1,23)=5.23$, $p<.05$, $\eta^2_p=.19$), location, ($F(1,23)=29.13$, $p<.001$, $\eta^2_p=.56$) and duration, ($F(2.9,67)=484.2$, $p<.001$, $\eta^2_p=.95$) and a significant interaction between modality and location, ($F(1,23)=22.8$, $p<.001$, $\eta^2_p=.5$). The effect of location seemed present only in the visual modality; separate repeated measures ANOVAs were conducted for the two modalities. The analysis in the visual modality found an effect of stimulus location, ($F(1,23)=28.25$, $p<.001$, $\eta^2_p=.55$), an effect of comparison duration, ($F(2.87,66.2)=146$, $p<.001$, $\eta^2_p=.86$) and a significant location by duration interaction, ($F(5.6,129.6)=4$, $p<.01$, $\eta^2_p=.15$). In conditions where the location of the comparison stimulus was different from the location of the standard there was a higher proportion of *longer* responses compared with the conditions where the stimulus locations were the same. Contrastingly, in the auditory modality only the effect of duration was significant, ($F(3.7,86)=565.9$, $p<.001$, $\eta^2_p=.96$).

PSEs for Experiment 3 are shown in Fig. 2f. The within subject ANOVA showed an effect of location ($F(1.98,45.6)=19.45$, $p<.001$, $\eta^2_p=.46$), and an interaction between location and modality, ($F(2.15,49.48)$, $p<.001$, $\eta^2_p=.41$). These results replicate the direction of the modality effect that we found in Experiment 2 but only for the locations LR and RL. T-tests showed that the value of the PSE at the visual LR ($\mu=270$) was significantly smaller than the auditory LR (μ=299), (t(23)=-4.47, p<.001, Cohen's d= -1.16) and the visual RL (μ=275) smaller than the auditory RL (μ=304), (t(23)=-3.9 p<.001, Cohen's d= -1.09). Also, visual LL (μ=329) was significantly different from auditory LL (μ=305) (t(23)=2.3, p<.05, Cohen's d= - .91), but the direction of the effect was the opposite, with the participants overestimating the duration of the auditory stimuli. The difference between visual RR (μ=315) and auditory RR (μ=308) was not significant. However the direction of the difference was the same as between visual and auditory LL. An additional within subject ANOVA was performed separately for each modality. The results showed an effect of location only in the visual modality, (F(3,69)=19.3, p<.001, η^2_p = .46.

Post-hoc pair-wise comparisons showed that visual LL was significantly different from visual RL, (t(23)=4.8, p<.001, Cohen's d=1.1) and LR, (t(23)=-5.1, p<.001, Cohen's d=1.23), and similarly, visual RR differed from visual LR, (t(23)=5.1, p<.001, Cohen's d=1.22) and RL, (t(23)=4.3, p<.001, Cohen's d=1.04).

WRs values appear to differ considerably between modalities (for the auditory conditions: μ=0.042 for LR, μ=0.041 for RL, μ=0.042 for RR and μ=0.039 for LL and for the visual conditions: μ=0.095 for LR, μ=0.095 for RL, μ=0.109 for RR and μ=0.096 for LL). This modality effect was confirmed by a within measures ANOVA, (F(1,23)=30.8, p<.001, η^2_p =.57).

3.4. Interim Discussion

The results of Experiment 3 confirmed the expectations that Experiment 1 and 2 raised, namely that participants tend to overestimate visual trials but only when the location of the comparison stimulus was different from that of the standard. In contrast, when the location was not changed participants tended to underestimate the visual trials. It should be noted that the overestimation bias in participants' perceived duration of visual stimuli was not observed in Experiment 1, when visual and auditory trials were presented in separate blocks. From the results presented thus far it cannot be decided whether this effect requires intermixed modality presentation. Thus, an additional experiment was conducted only in the visual modality in order to investigate the effect of location change in the absence of auditory trials.

4. Experiment 4

4.1. Introduction

Expeirment 4 used the same four location conditions as Experiment 3, but was conducted only in the visual modality. The overestimation of the *change of location* trials in Experiments 2 and 3 may be attributed to spatial attention shifts. If shifting visual attention is a sufficient cause of this bias in visual temporal performance, then we would expect to observe it in Experiment 4 too.

4.2. Methods

4.2.1. *Participants*

10 female and 7 male students of the University of Edinburgh from 18 to 30 years in age (M = 23.58, SD = 3.2) participated. The data of two participants were excluded from the analysis due to high levels of inaccurate responses (the criteria for exclusion were the same as in Experiment 1). Data from 15 participants were analysed.

4.2.2. Apparatus and Stimuli

The apparatus was the same as in the previous experiments with the exception that no auditory signals were generated or delivered.

4.2.3. Procedure

The structure of Experiment 4 was identical to the structure of the visual trials of Experiment 3. As only the visual block of trials was presented there was no cue indicating the modality of the trials. Participants performed 320 trials in total.

4.2.4. Data processing

Data processing was the same as in the previous experiments.

4.3. Results

Fig. 2g shows the psychophysical functions from the different location conditions with *same location* trials being combined and *change location* trials being combined, as in Experiment 3. As in the previous experiment, a rightward displacement of the *same location* function is apparent. A repeated measures ANOVA was conducted with location (RR, LL, LR and RL) and duration (10 comparison durations) as factors and found significant main effects of both location, ($F(1,16)=15.42$, $p<.01$, $\eta^2_p=.49$) and duration, ($F(2.7,43.8)=115.45$, $p<.001$, $\eta^2_p=.88$). *Same location* conditions elicited a lower proportion of *longer* responses than the *change of location* conditions, indicating an underestimation of the *same location* trials. PSEs for Experiment 4 are shown in Fig. 2h. T-tests showed that LL ($\mu=353$) was significantly different from both LR ($\mu=304$), ($t(16)=4.7$, $p<.001$, Cohen's $d=1.36$) and RL ($\mu=305$), ($t(16)=4.1$, $p<.001$, Cohen's $d=1.32$) and that RR ($\mu=333$) was different from LR, ($t(16)= -2.96$, $p<.01$, Cohen's $d= .96$) and RL, ($t(16)=2.8$, $p<.01$, Cohen's $d= .97$). These differences confirmed that participants underestimated *same location* trials compared to *change of location* trials. However, in this experiment, *change of location* trials were not overestimated, and their PSE values were close to the value of the standard stimulus (300). WRs were very similar across conditions. For *change of location* $\mu=0.095$ for LR and $\mu=0.099$ for RL, and in *same location* conditions $\mu=0.107$ for RR and $\mu=0.084$ for LL.

4.4. Interim Discussion

The only significant effect to be observed in Experiment 4 was a large underestimation of the comparison stimulus in *same location* trials. The fact that an absolute overestimation of *change of location* trials was not observed in this experiment (but had been in the earlier experiments) suggests that spatial attention shifts may not be the only factor underlying this effect.

5. Experiment 5

5.1. Introduction

An effect that has been absent from most of the reported results is the tendency for auditory stimuli to be judged as longer than visual events of the same duration. Since all the comparisons in Experiments 1 -3 have been within modality, we did not expect to observe a strong effect. In order to make it possible for a proper conclusion regarding the “sounds seem longer than lights effect” to be reached, we conducted a final experiment that was designed to include cross-modal comparisons. The structure of Experiment 5 was similar to that of the first experiment described by Wearden, Todd & Jones (2006). In that experiment they used uni-modal and cross-modal presentations. The cross-modal judgements depended upon which modality was used as the standard and which was the comparison. Thus, judgements where the standard was an auditory stimulus resulted in the visual event being judged as shorter, while the reverse situation led to auditory events appearing longer. With this effect well established for centrally presented stimuli the current experiment continued to investigate the impact of stimulus location changes.

5.2. Methods

5.2.1. *Participants*

Twenty-eight participants, 15 female and 13 male from 19 to 30 years in age ($M = 23.2$, $SD = 3.1$) were recruited. The data of three participants were excluded from the analysis due to high levels of inaccurate responses (the criteria for exclusion were the same as in Experiment 1). Data from 25 participants were analysed.

5.2.2. Apparatus and Stimuli

The apparatus was the same as in the previous experiments although the sequencing of stimuli was different for cross-modal judgements.

5.2.3. Procedure

There were four different forms of standard-comparison sequence; using V for visual and A for auditory they were as follows: V-V, A-A, V-A and A-V. Additionally, two levels of standard-comparison location were used: LR or RL, yielding eight different presentation conditions. For each of these the standard stimulus used the same 300 ms duration throughout. There followed a 250 ms ISI, and this was followed by one of the ten comparison durations of earlier experiments. Each of these eighty stimulus combinations was presented eight times, so that participants performed 640 trials in total. The different trial types were randomly intermixed and no cue was used to indicate the modality of the following trial.

5.2.4. Data processing

Data processing was the same as in the previous experiments.

5.3. Results

Fig. 2i shows the psychophysical functions from the different location conditions LR/RL trials being combined. A repeated-measures ANOVA was conducted with modality (V-V, A-A, V-A and A-V), location (LR vs RL) and comparison duration (10 levels) as factors. Modality ($F(3,72) = 25.05$, $p<.001$, $\eta^2_p = .51$), location ($F(1,24) = 7.79$, $p<.05$, $\eta^2_p = .24$) and comparison duration ($F(2.2,52.8) = 346.5$, $p<.001$, $\eta^2_p = .93$) were all found to have a significant effect on the proportion of longer responses. Also, the interaction between modality and duration was significant, ($F(11.2,270.5)=18.78$, $p<.001$, $\eta^2_p = .44$). Separate repeated measures ANOVAs were conducted for the different modality conditions. The analysis in the A-A condition showed an effect of location ($F(1,24)=4.61$, $p<.05$, $\eta^2_p = .16$) and an effect of comparison duration ($F(3.37,80.9)=233.56$, $p<.001$, $\eta^2_p = .9$). The LR location condition elicited a higher proportion of *longer* responses than did the RL condition. Both effects of location ($F(1,24)=4.8$, $p<.05$, $\eta^2_p=.17$) and comparison duration ($F(4.2,2101.3)=4.61$, $p<.05$, $\eta^2_p=.16$) were also found significant in the A-V cross-modality condition. This condition also produced a higher proportion of *longer* responses in LR than in RL. In contrast, the ANOVAs in the V-V and in the V-A conditions found only an effect of comparison duration ($F(3.6, 86.6) = 122.52$, $p<.001$, $\eta^2_p=.83$ and $F(3.5, 83.3) = 263.36$, $p<.001$, $\eta^2_p=.92$ respectively); there was no location effect.

Fig. 2j shows the PSEs for the different modality conditions. The within subject ANOVA showed both an effect of modality ($F(1.7, 41.2) = 21.95$, $p=.001$, $\eta^2_p=.48$) and location ($F(1,24) = 6.36$, $p<.05$, $\eta^2_p=.21$). Post-hoc pair-wise comparisons using the Bonferroni adjustment showed that the A-V condition (M=345.26, SE = 9.6) elicited significantly higher PSE values ($p<.001$) than the V-A (M=290.5, SE = 4.15), but so it does when compared with the V-V (M=285.76, SE =4.87) and A-A (M=296.6, SE=4.29). The other conditions do not differ significantly from each other, however there is a trend for a difference between V-V and AA conditions. Post-hoc t-tests showed a significant difference between V-V RL ($\mu=287$) and A-A RL ($\mu=299.5$) ($t(24) = -2.39$, $p<.05$) but not between V-V LR ($\mu=285$) and A-A RL ($\mu=292$). Also apparent is a hint of the horizontal position effect, with RL sequences resulting in a higher PSE than the LR. T-tests performed as post-hoc tests demonstrate a significant effect of location only between A-A LR and A-A RL, ($t(24)=-2.58$, $p<.01$, Cohen's $d=-0.41$).

A within subject ANOVA on the WRs showed an effect of modality ($F(1.15, 27.67)=22.75$, $p<.001$, $\eta^2_p=.49$). Post-hoc pair-wise comparisons using the Bonferroni adjustment showed that conditions A-A (M= .042, SE = .006) and V-A (M=.044, SE =.005) were eliciting lower WR values ($p<.001$) than both V-V (M=.106, SE =.014) and A-V

(M=.084, SE=.007), indicating that participants' performance in V-V and A-V was poorer than in A-A and V-A.

5.4. Interim Discussion

This experiment provided evidence for the "sounds are judged as longer than lights" effect with participants overestimating the V-A conditions in comparison to the A-V. Thus, the crossmodal trials of Experiment 5 supported the findings from the crossmodal trials of Wearden et al. (2006). In contrast, the unimodal trials (V-V and A-A) showed once again the effect that was observed in our previous mixed modality experiments (2 and 3), i.e. the overestimation of the visual trials in comparison to the auditory ones. A left/right difference was observed in this experiment. However, this phenomenon was observed only for intra-modality comparisons and this only in the auditory domain.

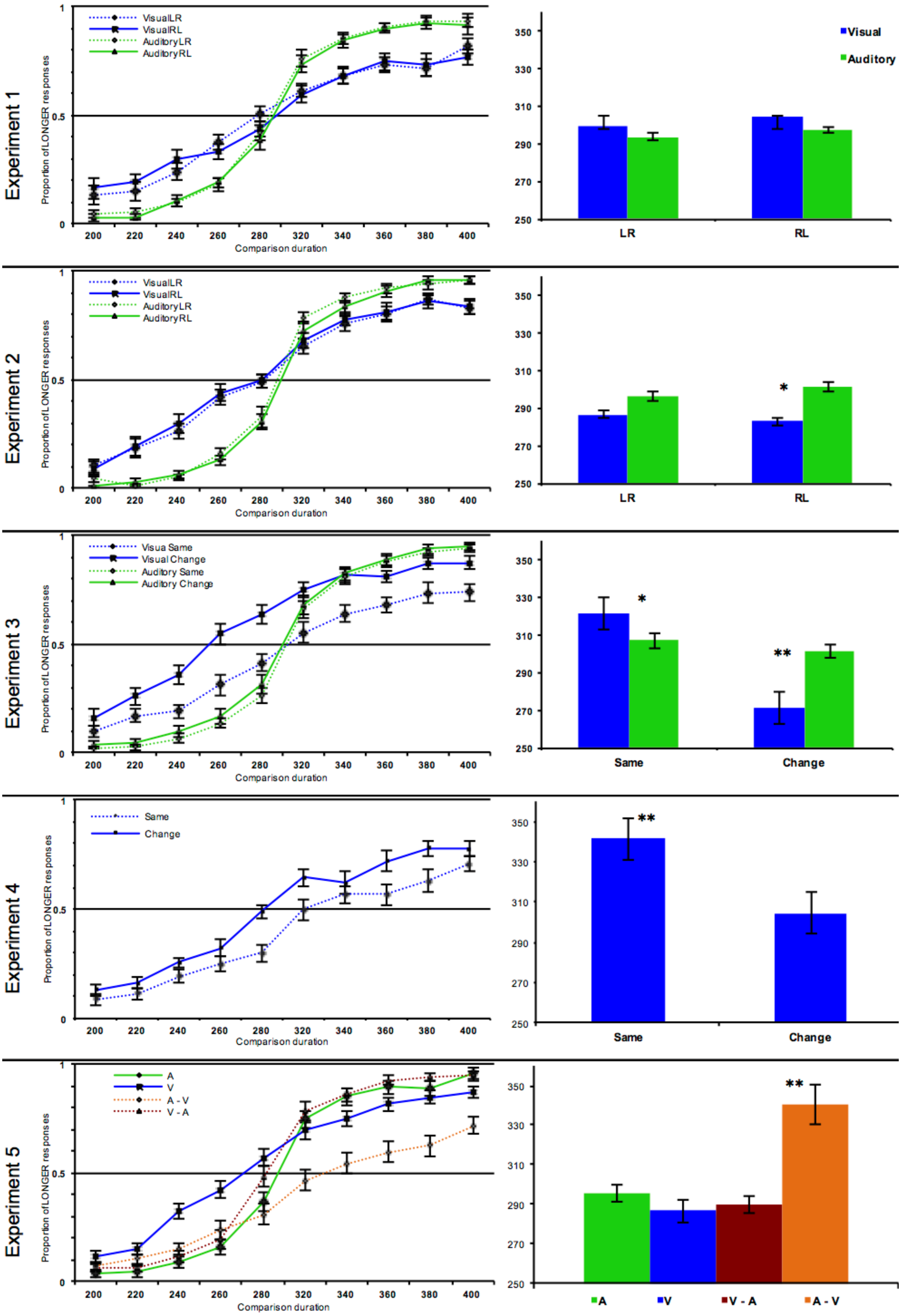
Experiment 1
Proportion of LONGER responses
VisualLR
VisualRL
AuditoryLR
AuditoryRL
Comparison duration
Visual
Auditory
LR
RL
Experiment 2
Proportion of LONGER responses
VisualLR
VisualRL
AuditoryLR
AuditoryRL
Comparison duration
LR
RL
Experiment 3
Proportion of LONGER responses
Visua Same
Visual Change
Auditory Same
Auditory Change
Comparison duration
Same
Change
Experiment 4
Proportion of LONGER responses
Same
Change
Comparison duration
Same
Change
Experiment 5
Proportion of LONGER responses
A
V
A - V
V - A
Comparison duration
A
V
V - A
A - V

Fig. 2. The left side of this figure illustrates psychophysical functions (mean proportion of LONGER responses plotted against comparison stimulus duration) for Experiments 1 – 5 (a, c, e, g & i) while the right side illustrates mean Points of Subjective Equality from the different modality and location conditions of Experiments 1 – 5 (b, d, f, h & j). Standard errors are indicated by vertical lines. Asterisks in 2b, d & f indicate significant differences between the modality conditions and in 2h indicate significant differences between location conditions.

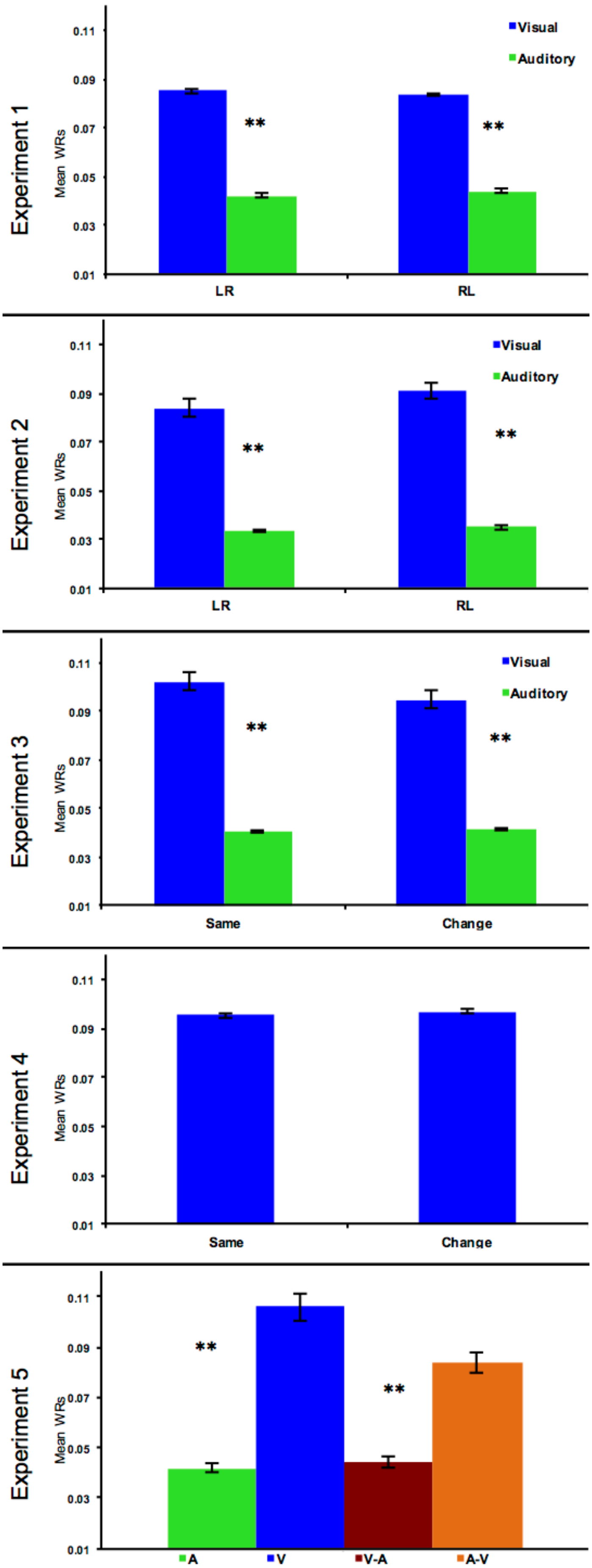
Experiment 1
Mean WRs
0.11
0.09
0.07
0.05
0.03
0.01
Visual
Auditory
**
**
LR
RL
Experiment 2
Mean WRs
0.11
0.09
0.07
0.05
0.03
0.01
Visual
Auditory
**
**
LR
RL
Experiment 3
Mean WRs
0.11
0.09
0.07
0.05
0.03
0.01
Visual
Auditory
**
**
Same
Change
Experiment 4
Mean WRs
0.11
0.09
0.07
0.05
0.03
0.01
Same
Change
Experiment 5
Mean WRs
0.11
0.09
0.07
0.05
0.03
0.01
**
**
A
V
V-A
A-V

Fig. 3. This figure illustrates the mean Weber Ratio values from the different modality and location conditions of Experiments 1 – 5. Standard errors are indicated by vertical lines. Asterisks indicate significant differences between the conditions.

6. General Discussion

Five experiments were conducted in order to determine the influence of modality and location on duration judgments. In all experiments involving mixed modality presentation (Experiments 1, 2, 3 and 5) participants showed higher temporal sensitivity in the auditory modality compared to the visual. Moreover, participants' higher discrimination performance in the auditory modality was independent from the general cognitive demands of the task (mixed or blocked modality presentation and number of spatial locations). This finding highlights the dominance of the auditory domain in duration judgments (Lapid, Ulrich & Rammsayer, 2009).

Previous studies have reported longer temporal judgments associated with the right side of space and shorter temporal judgments associated with the left side of space (Vicario, 2008). However, no effect of location per se was observed in our experiments (with the exception of the A-A condition of Experiment 5). This finding was surprising considering that the procedure of our experiments (especially of Experiment 1) was identical to the one used by Vicario et al., 2008. There is evidence that representation of time in terms of a MTL is highly dependent on cultural factors such as the experience of reading or writing (Bottini et al., 2015). It could be the case that the educational/cultural background of our participants led into a weak association between magnitude and the horizontal continuum, although there is no direct evidence to support this. It should be noted in this context that the current study had more power than the previous one reporting the left/right differences on duration judgments (Vicario et al., 2008). These discrepancies between the results of our study and the previous ones highlight the importance of inter-individual variability in duration judgments which would be interesting to explore in future studies.

Instead of an effect of location per se, an effect of change of location was observed in visual conditions; participants tended to overestimate the duration of the comparison stimulus when presented in a different location from the preceding standard.

The first experiment served to provide a baseline. The conditions were blocked and the second stimulus was presented in a different location from the first. In these circumstances the PSEs were all close to the true point of equality, and the only difference between the modalities was that the steeper response curve for auditory stimuli showed this system to be capable of finer discrimination. Although accuracy in the visual modality was worse than in the auditory, there was no consistent bias for under or over estimation. Subsequent experiments examined the impact of various manipulations on this baseline.

The first manipulation (Experiment 2) consisted of mixing the stimuli, so that auditory and visual trials were no longer blocked. The results showed that the psychophysical functions retained their general form, but for the visual stimuli they moved to the left. In other words, the PSE decreased as a result of increased overestimation of visual stimuli. Previous studies have provided evidence for the inverse effect, i.e. overestimation of auditory temporal judgments when intermixed with visual judgments in the same session (Wearden, Todd & Jones, 2006; Penney, Gibon & Mech, 2000).

It is worth re-emphasising that previous studies investigating modality differences in duration perception involved central location presentation of visual and auditory stimuli. In our experiments, the visual stimuli were presented in two different spatial locations. Therefore, participants had to monitor two different locations and shift their attention between them. Shifts of spatial attention have been found to affect subjective duration (Cicchini & Morrone, 2009; Yeshurun & Marom, 2008; Chen & O'Neill, 2001; Pouthas &

Perbal, 2004). Thus, there was the possibility that using separate locations for the standard and comparison stimuli, as we did in our experiments, produced different results from those that would have been obtained with a single location. Experiment 3 addressed this issue by mixing same and separate location conditions, both for visual and auditory stimuli. As in Experiment 2, the visual stimuli elicited lowered PSEs, but only when the standard and comparison were in different locations. When both occurred in the same location, observed PSEs were higher. Experiments 2 and 3 appear to have established that, in the visual modality, if standard and comparison stimuli are located in different regions, the latter will be estimated as relatively longer. However, this contrasts with Experiment 1, where perceptions appeared to be veridical. The experiments described so far suggest that it is possible that the assessments in the visual modality were in some way influenced by the intermixing with auditory trials. To test this, Experiment 4 repeated the use of same and different location conditions, but presented only visual stimuli. Here, no overestimation of *change of location* trials was found – regardless of the number of locations. Underestimation of *same location* trials was still observed though, as in Experiment 3.

6.1. Overestimation Bias

In Experiments 1 - 4, the overestimation of visual trials in the *change of location* condition was apparent only when visual and auditory trials were intermixed. When visual and auditory trials were presented in separate blocks (Experiments 1 and 4) no overestimation of change of location was found. Switching between the two modalities seems to result in differences in temporal processing. In order to explain this overestimation of visual stimuli in the change of location condition, we propose that there is an error-correction mechanism at work, which manifests differently under different conditions. The role of this mechanism is to compensate for a loss of time, which results from spatial shifts of attention. Thus we hypothesize that when spatial attention is shifted from one location to another, this causes some loss of time; in terms of a clock model, this would be due to pulses being lost or forgotten during the spatial attention shift. In order to compensate for this loss of time, a certain duration is added to the estimation.

This error-correction mechanism is similar to the compensation mechanism proposed by Yarrow et al. (2001), which specifically corrects for time lost during saccades. In the case of the saccadic effect, an overestimation of the duration of visual stimuli following saccades is observed (referred to as chronostasis). Both compensation mechanisms facilitate relatively accurate duration discrimination. Unlike the saccadic mechanism, which results in an apparent bias whenever a saccade is involved, the error-correction mechanism proposed here works seamlessly under most circumstances (i.e. when only visual trials are presented in the session). However, when visual and auditory trials are intermixed, it seems that this error-correction mechanism is affected and possibly getting over-activated (adding a larger duration than needed) leading to the apparent overestimation bias.

Research on multisensory integration has shown that the presentation of a stimulus in one sensory modality can alter the perception of a stimulus in a second sensory modality (Stevenson, Zemtsov & Wallace, 2012). Incongruent, task-irrelevant auditory stimuli alter the duration perception of concurrently presented visual stimuli (Bausenhart et al. 2014, Romei et al., 2011), and auditory signals presented in close temporal proximity to visual signals affect the performance on TOJs (Hairston et al. 2006). Multisensory interactions of audio-visual signals are highly dependent on their temporal and spatial relationship, with more temporally coincident stimuli leading to larger interactions (Stevenson et al. 2013; Hillock, Powers & Wallace, 2011). It is conceivable that a certain integration of the auditory and visual signals occurred in our mixed modality presentation experiments which contributed to the observed biases. When different modalities were presented in the same session their output was combined despite the fact that it was not required by the task. So apart from having to deal with the spatial attention shifts between the different locations where the visual stimuli are presented, a combination/comparison of the output of the visual and auditory “clocks” may have also taken place.

The overcompensation could result from the differences in speed between the visual and auditory “clocks”. It has been suggested that when visual and auditory trials are presented within the same session, a common standard is formed in memory (dominated by the auditory standard) and this results in underestimation of visual trials (Penney, Gibbon & Meck, 2000). Previous studies have provided evidence that the auditory pacemaker runs faster than the visual one (Chen & Yeh, 2009; Klink et al., 2011). The overcompensation that was described above could thus be a result of the faster speed of the auditory clock, according to which it is assumed that even more time needs to be added in the visual change of location trials. In other words, interference from the auditory domain causes the temporal error in the visual domain to be overestimated, and so overcorrected for.

The fact that the overestimation bias seems to be more prominent in Experiment 3 – where participants were required to alternate between different modality trials and shift their attention accordingly - than in Experiment 2 may suggest that the experiment’s cognitive load is also affecting this mechanism. Cognitive load has been found to affect temporal performance with duration judgments (Block, Hancock & Zakay, 2010). Thus, an alternative hypothesis concerning the present results could be that it is not specifically the mixing of two modalities that leads to the overestimation effect but rather a more general effect of the higher attentional demands of this paradigm where participants have to switch their attention between different modalities. This hypothesis would be supported by the observation of this effect increasing when there are more location conditions (as in Experiment 3), and therefore higher demands on attentional resources.

It should be noted that fixation was not monitored in the current experiments. Despite the fact that participants were asked to fixate on the central cross, it is still possible that they sometimes were moving their eyes. Thus, we cannot rule out an explanation based on saccadic movements (‘chronostasis’). However, the fact that the observed overestimation of *change of location* visual trials only appeared in the mixed modality experiments (2, 3 and 5) and not in experiments 1 and 4 makes an explanation solely based on eye movements less likely.

6.2. Underestimation Bias

Furthermore, an underestimation of the same location trials was observed in Experiments 3 and 4. The underestimation of visual *same location* trials was firstly observed in Experiment 3, and was initially attributed to the previously reported visual – auditory differences in perceived duration (“sounds are judged as longer than lights”). However, this underestimation bias was replicated in Experiment 4 where only visual trials were presented. Therefore, this bias seems to be independent of the modality mixing but rather dependent on the mixing of different location conditions, as it appears when change of location and same location visual trials are intermixed in the same session. The presently observed underestimation of the same location trials could be a manifestation of an Inhibition of Return (IOR) effect (i.e. stimuli presented at previously attended locations tend to be processed less efficiently) (Wang & Theeuwes, 2012; Klein, 2000).

Underestimation of duration of stimuli that appear at the same location as the standard has also been reported in local adaptation experiments (Johnston, Bruno & Ayhan, 2011). In the case of the adaptation to drifting motion or to flickering, the duration of comparison stimuli presented on the adapted spatial location was reduced. However, in the present experiments the short duration of the presentation of the standard stimulus (300 ms) makes this interpretation of the data unlikely. Although, the present data suggest that these two biases are possibly caused by two separate mechanisms that superimpose under certain conditions (as modality mixing), further experiments are needed in order to clarify how these biases relate.

6.3. "Sounds are judged as longer than lights"

Experiments 1 - 4 used either blocked or mixed modality presentation design, however all trials were unisensory (a visual standard was always followed by a visual comparison and an auditory standard by an auditory comparison). The previously reported "sounds are judged as longer than lights" effect has been observed more strongly in cross-modal trial presentation (Wearden et al., 2006). Thus, Experiment 5 included both unisensory and cross-modal trial presentations in order to further explore the effect of modality and location changes.

The results of Experiment 5 showed evidence of the "sounds seem longer than lights" effect. Specifically, trials where an auditory stimulus was compared with a visual standard (V-A) were overestimated compared to trials where a visual stimulus was compared with an auditory standard (A-V). However, in uni-modal conditions visual trials were overestimated compared to auditory, as was observed in our previous experiments.

In Experiment 5 participants clearly found the A-V sequences particularly difficult. The WR in this condition was 0.84, whereas in the V-A condition sensitivity was almost twice as good with a WR of 0.44. This may be compared with the equivalent experiment of Wearden *et al.* (2006) where the ratios were 0.36 and 0.35 respectively. Grondin (2014) reported that empty duration intervals, marked by two stimuli – instead of filled as we did – were easier to discriminate when the first and second signal markers of the duration intervals were crossmodal compared to when the markers were unimodal. However, there was no reported difference in performance between A-V and V-A trials. The difference in the current study may be attributed to the location changes from standard to comparison; Wearden *et al.* and also Grondin, had used central stimuli. We hypothesise that the difficulty introduced for our participants resulted from the tendency to link auditory and visual events. It is relatively easy for sound to "follow" vision, as demonstrated by the ventriloquism effect (Klink, Montijn & van Wezel, 2011). In contrast, we argue, visual attention is not easily detached from the location of an auditory event. As a consequence, it is not too difficult for participants to "map" the sound onto a different visual location in V-A sequences, and produce a reasonably accurate duration estimate. However, having heard a sound in one location, significant time is lost in acquiring and assessing the duration of a visual event elsewhere. We suggest that it is for this reason that A-V sequences led to less sensitive judgments and also produced such elevated PSEs. In this context it should be mentioned that many participants reported in post-experimental debriefing that they found the task easier if they imagined each visual stimulus as a sound, then tried to judge how long that lasted. Surprisingly, this strategy was reported even in Experiment 4, where only visual stimuli were used. This implied light to sound conversion is consistent with the findings of a recent TMS study over the primary visual and auditory cortex showing a modality-independent role of primary auditory cortex in time estimation (Kanai et al. 2011). This hypothesis could be further investigated by employing concurrent vocalisation, in an attempt to disrupt the conversion process, just as it has been used to impair grapheme-to-phoneme conversion in research on reading (Mayer, Crowley & Kaminska, 2007).

Regarding the clock theories of time perception, our results suggest that it is likely that the internal "clock" is closely associated with the most reliable modality, i.e. audition. Consequently, if an auditory stimulus is to be judged the process is rather direct, and the result is accurate and consistent. The visual timing tasks of the sort we used in our experiments then may be performed by referencing the same clock as used by the auditory system. One means by which this can be achieved is by imagining an auditory stimulus, lasting for the duration of the visual event. In a stable situation, like in visual blocked modality presentations, where there is no interruption from direct use of the auditory system, the outcome is similar in overall accuracy to that of auditory assessments, although consistency is inferior, i.e. the WR is larger. However, with its indirect use of the auditory clock, the visual timing system is more vulnerable to the impact of attentional effects, and what we have termed overcorrection, apparent when shifting visual locations, may be an example of this. It is possible that, in certain situations, such as when the stimuli are dispersed in space, these include a left-right effect, suggestive of a time- or number-line. This could result from a conflict between the "anchor" modality – audition for timing and vision for spatial processing. Further studies will be needed to elucidate the exact nature of these phenomena and factors determining their appearance.

One limitation of the current study is that we used a fixed ISI instead of a variable one. That, combined with the fact that the standard stimulus was always presented first could result in participants making single duration judgments (long – short) instead of comparing the second stimulus to the standard. If participants were using this strategy, they would still need to make temporal judgments by using an implicit standard duration of 850 ms. In that case the task would be more difficult and result in less precise judgments according to Weber's law. It is also worth mentioning, that a recent study investigated the effects of the type of ISI (constant versus variable) in a duration discrimination task, very similar to the tasks presented here, and found no differences in perceived duration, discrimination sensitivity and reaction times between the two types of ISIs (Birngruber, Schroter & Ulrich, 2015). However, in future research it would be advisable to use a variable ISI in order to be able to examine how this can affect the present duration judgments.

7. Conclusion

In conclusion, the present findings shed light on the effects of spatial location within temporal processing. Our experiments demonstrated that duration judgments are modulated by change of location. We observed an overestimation in change of location conditions and underestimation in those where the same location was maintained. We argue that the overestimation bias is the result of a mechanism compensating for the loss of time that occurs during spatial attention shifts between the two different locations, by adding a specific duration. This mechanism facilitates the relatively accurate duration discrimination observed in the visual change of location conditions. However, this mechanism is over-activated under some circumstances – such as mixed modality - resulting in a systematic bias. We suggest that this bias provides evidence for an automatic interference between visual and auditory duration representations. The present error-correction mechanism is an essential feature of spatio-temporal awareness, facilitating the unified and coherent experience of time.

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